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Where does hydrogen fit in a sustainable energy economy?

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Abstract

Where does hydrogen fit into a global sustainable energy strategy for the 21st century, as we face the enormous challenges of irreversible climate change and uncertain oil supply? This fundamental question is addressed by sketching a sustainable energy strategy that is based predominantly on renewable energy inputs and energy efficiency, with hydrogen playing a crucial and substantial role. But this role is not an exclusive one as in the original concept of the 'hydrogen economy' proposed in the early 1970s. A hierarchy of spatially-distributed hydrogen production, storage and distribution centres relying on local renewable energy sources and feedstocks would be created to avoid the need for an expensive long-distance hydrogen pipeline system. There would thus be complementary use of electricity and hydrogen as energy vectors. Importantly, bulk hydrogen storage would provide the strategic energy reserve to guarantee national and global energy security in a world relying increasingly on renewable energy; and longer-term seasonal storage on electricity grids relying mainly on renewables. In the transport sector, a 'horses for courses' approach is proposed in which hydrogen fuel cell vehicles would be used in road and rail vehicles requiring a range comparable to today's petrol and diesel vehicles, and in coastal and international shipping, while liquid hydrogen would probably have to be used in air transport. Plug-in battery electric vehicles would be reserved for shorter-trips. Energy-economic-environmental modelling is recommended as the next step to quantify the net benefits of the overall strategy outlined.

Keywords: hydrogen economy; global sustainable energy strategy; renewable energy; fuel cell vehicles; battery vehicles; energy storage; energy security

1. Introduction

Now that we confront the three-pronged threat of irreversible climate change, a deficit between oil demand and supply, and rising levels of pollution generally, the original (Hydrogen Economy) HE concept needs re-envisioning. Significant developments in battery technology, with lithium ion and lithium polymer batteries (e.g. higher gravimetric and volumetric energy densities than traditional lead acid batteries) [1] help speed up the process of battery electric vehicle (BEV) commercialisation. If electric vehicles are to be a true zero-emission mode of transport, however, the electricity for battery charging must come from renewable energy (RE) sources of electricity (or the more problematic nuclear, or fossil fuel power stations with carbon capture and storage). Yet the very same is the case for the electricity to produce hydrogen by electrolysis, the most likely early production technology, for use in hydrogen fuel cell vehicles. Why then traverse the apparently more circuitous and energy lossy route of converting electricity to hydrogen, transporting and storing it, and then reconverting it back to electricity on board a vehicle in a fuel cell, rather than simply charging batteries in vehicles using

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grid electricity generated from renewables? With batteries, it is electricity in and electricity out directly from the one electrochemical device.

Another alternative that has emerged to hydrogen as a transport fuel is biofuel, including principally ethanol, various bio-oils and biodiesel. Provided the energy used to produce and distribute these biofuels is obtained from renewable resources, they are a zero-emission option like hydrogen produced from renewables. Using biofuels for transport needs relatively minor changes to existing engines and fuel distribution infrastructure. To many, biofuels are thus seen as a much more readily implementable substitute for petroleum fuels than taking on the apparently herculean challenge of switching to hydrogen, which indeed would require a completely new fuel distribution, storage and dispensing infrastructure, as well as a radical change in vehicle motive power systems and associated vehicle design.

The original vision for such a HE [2] was conceived at a time when concerns about running out of oil, natural gas, and ultimately coal in the face of exponential growth in global primary energy use, and the associated rising pollution levels, were first being raised [2, 3]. In the original hydrogen economy (HE), hydrogen further played the critical role of providing the energy storage that would allow continuous base-load electricity supply in a system relying substantially on intermittent and variable renewable energy (RE) sources such as solar, wind and ocean power. In recent years this role for hydrogen too has come under strong challenge from a number of alternatives, including batteries, super-capacitors, thermal storage, and multiple RE inputs geographically distributed over a large-scale grid. Bockris in his 1975 book [2] does refer to the fact that increasing coal consumption could lead to increasing carbon dioxide in the atmosphere and global warming. But it is a cursory mention, since the threat of looming climate change was then only dimly recognized, and in no way a driving force behind the transition to a HE as it is today.

It is our view that the original HE concept now needs radical re-envisioning. A number of important strategic hydrogen energy studies have been conducted over the past decade (such as International Energy Agency [4], HyWays [5], Dougherty et al. [6], and National Hydrogen Association [7]. In the present paper, we draw upon these studies, together with Andrews' preliminary sketch of a sustainable hydrogen economy [8] and a more comprehensive one in Andrews and Shabani [9], to argue that, rather than seeing hydrogen as the exclusive fuel for the future, the specific roles to which it is uniquely suited in each major sector within an overall sustainable energy strategy need to be identified. With this approach we expect that hydrogen would still play a substantive and crucial role, but *a role in concert* rather than competition with that of electricity and technologies such as BEVs and a variety of shorter-term energy storage options for grid power.

2. Renewable Energy sources to meet total global energy demand

The fundamental question is that whether there are sufficient RE sources (solar, wind, wave, tidal, hydro, biomass and geothermal) available, and economically deployable, to meet global energy demands, while forecast population growth and rises in material standards of living, particularly in developing countries are taken into account. The potential resource constraints in a sustainable HE based on RE sources were investigated by Kleijn and van der Voet [10]. They estimated that the primary energy requirements of a global economy in 2050 that were 2.5 times those in 2005 could be met entirely from potentially collectable solar radiation (80% of the total supply), wind power (15%) and other renewables (5%). However, it was pointed out that the infrastructure to harvest that amount of RE would require massive investments, and that extensive transmission networks may be necessary since optimal energy harvesting locations are often far from the centres of consumption. A highly decentralised sustainable energy economy along the lines suggested in the present work was not considered.

Jacobson and Delucchi [11] have recently completed one of the most thorough studies to date into the potential of Wind, Water and Sunlight (WWS) energy sources to provide the primary energy required by a global sustainable energy economy in 2030. Referring to US Energy Information Administration (2008) projections , Jacobson and Delucchi [11] base their scenarios on the current average world rate of energy consumption for all end-uses rising from 12.5 TW (1012 W) in 2008 to 16.9 TW in 2030 on the basis of the current range of primary fuels employed, primarily fossil fuels, nuclear and a small contribution from renewables. However, they estimate that a shift to renewable WWS sources to replace all fossil fuel and wood combustion by 2030, together with a shift to electricity and hydrogen as energy carriers, and strong energy efficiency measures in all sectors, could reduce the global demand to be met in that year to just 11.5 TW, that is, 8% less than in 2008. Jacobson and Delucchi [11] show how this demand could be met entirely from WWS sources including wind, wave, hydro, geothermal, photovoltaic and solar thermal power technologies (Fig. 1). The estimated total new land area – excluding land already used for renewables such as hydroelectric plants, and the space occupied by off-shore wind, wave and tidal power devices – would be only 1% of the total global land area, and hence in principle potentially feasible [11].

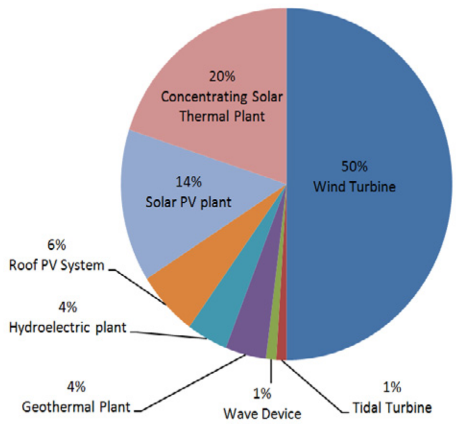

Fig. 1. The mix of RE sources proposed by Jacobson and Delucchi [11] to meet the total global energy demand in 2030

In the sustainable energy strategy to be proposed here, no reliance is placed on nuclear fission power or carbon capture and storage (CCS). High economic costs; political obstacles; long lead times to operation; the lack of a safe method of storage and disposal of high-level radioactive wastes; the serious risks of the release of harmful radiation from operating nuclear reactors, particularly in the event of natural disasters, terrorist attacks, or war; the inexorable connection between a peaceful nuclear fission power program and the proliferation of nuclear weapons; and the 9-25 times more carbon emissions of nuclear energy compared to wind energy [12, 13], are the main reasons for eschewing nuclear power. As for CCS, it is unlikely that sufficient geological formations near to coal-fired power stations with the requisite properties to hold carbon dioxide without its return to the atmosphere at any time will be found. The economics of coal-fired power stations become unfavourable once the full costs of CCS are counted [11].

3. Re-envisioning the role of hydrogen in a sustainable energy strategy

The re-envisioned HE, which we call here ‘Hydrogen In a Sustainable Energy’ (HISE) strategy, is set firmly in the context of a zero greenhouse gas emission economy in terms of both the production of hydrogen from renewables and consumption, rather than just as a response to depleting reserves of fossil fuel. HISE involves decentralised distributed production of hydrogen from a wide variety of renewables and feedstocks and there is no long distance transmission of hydrogen via pipelines to centres of consumption. In HISE, hydrogen and electricity play complementary roles as energy vectors, and hydrogen and batteries complementary roles as energy stores, in the transport sector and industrial, commercial and residential sectors – no longer is hydrogen the sole and exclusive energy carrier and store in every sector of the economy. As also discussed earlier, HISE does not accept nuclear fission power input and focuses exclusively on renewables, coupled with an equally strong emphasis on energy efficiency and demand management, in an overall sustainable energy strategy akin to that espoused over many years by Amory Lovins and his coworkers [14, 15]. In HISE hydrogen is used for longer-duration energy storage on centralised grids relying extensively on RE inputs and bulk hydrogen storage is also employed as the strategic energy reserve to guarantee national and global energy security in a world relying increasingly on RE [9].

A hierarchy of distributed sustainable hydrogen production, storage and distribution centres is shown in (Fig. 2). Based on the available sources and distribution of RE (depending on the local conditions in a particular country or region) as well as desirability of producing hydrogen near to where it is consumed, the following principal types of centre would be expected: off-shore, coastal, inland, and autonomous in this hierarchy.

The primary role of off-shore hydrogen centers (OHCs) would be to produce hydrogen from wave, tidal stream, and/or wind power on a very large scale by electrolysis of sea water, particularly for the transport sector. Hydrogen can also be stored from season to season and be supplied to large-scale fuel-cell power plants to provide the back-up electricity input to the centralized grid to ensure continuous supply throughout each year as primary energy inputs from renewables fluctuated. In OHCs can feed power directly to the main grid and the surplus to electrolysers for hydrogen production (see for example, Floating Power Plant [16]).The theoretical wave power potential globally is estimated to be up to 9 TW [17] with about 2

TW potentially exploitable [17], which is about the same as the 2008 total world electricity demand of around 2 TW [18]. Some of the hydrogen produced by OHCs would be pumped via pipelines for direct on-shore usage and storage in on-shore facilities, but there is also the intriguing and potentially attractive opportunity of storing hydrogen in very large quantities in subsea depleted natural gas or oil reservoirs. This option was studied by Foh et al. [19] and Taylor et al. [20], and judged then to be technically feasible, though little work has been done on this approach more recently. Taken together these off- and on-shore bulk hydrogen storage facilities could play the crucial strategic role of ensuring continuity of supply to the transport and centralised electricity generation sectors, as an increasingly high proportion of total primary energy demand is met from intermittent and variable RE sources. A further critical role of these bulk hydrogen storages would be to provide the national (and in some locations possibly international) energy reserves needed to guarantee energy security, in the face of disruptions to supply.

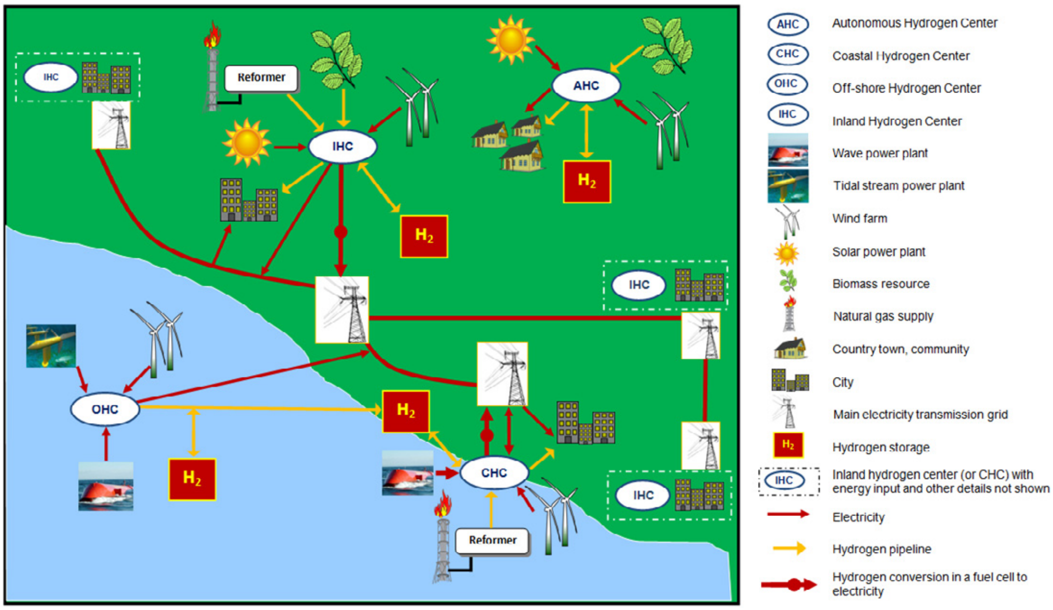

Fig. 2. A schematic illustration of the proposed hierarchy of sustainable hydrogen centres showing the principal RE inputs to each type of centre, the local hydrogen distribution system, and the interconnection of higher-order centres via the main electricity grid [9].

Coastal hydrogen centres (CHCs) would be located on land near the sea. The wind and wave power sources would supply electricity to the main grid, and produce hydrogen from water on a very large scale in electrolysers [21, 22]. This hydrogen would supplement the supply from OHCs and other sources to meet the ongoing requirements of the transport sector. Some would also be stored from season to season, and if needed for shorter terms, to feed to large-scale fuel-cell power plants to provide the back-up electricity input to the centralized grid to ensure continuous supply throughout each year as direct electricity supply from renewables varies. The principal on-shore options for bulk storage of hydrogen underground in pressurised gaseous form are depleted natural gas or oil reservoirs, aquifers, excavated rock caverns, and solution-mined salt caverns. All these underground storage methods for bulk storage of hydrogen were investigated by Foh et al. [19] and Taylor et al. [20], and found to be technically feasible and among the lowest-cost options for bulk storage. In addition or alternatively, the main options for land-surface-based large-scale hydrogen storage facilities are compressed gas facilities at pressures up to 700 bar, bulk solid-state storage facilities based on metal or chemical hydrides, or carbon-based materials [23]. The demand for electricity from the main grid will also rise as BEVs are increasingly introduced and used for shorter trips, in a complementary way with hydrogen-fuelled vehicles for those requiring a larger range.

The main RE resources used in inland hydrogen centres (IHCs) are likely to be solar radiation, used for production of electricity in photovoltaic, or solar thermal systems producing electricity (via a heat engine of some kind) and heat; wind power; biomass resources of various kinds; and in certain areas geothermal energy too. Such IHCs would provide geographically-distributed sources of hydrogen supply for the road and rail transport sector, and fuel-cell power plants to supply back-up electricity to the centralised grid. As with CHCs, IHCs would generally be located close to inland cities and centres of industrial and agricultural production to provide a local source of hydrogen supply for transport – road, rail and air – and back-up grid supply via fuel cell power stations without having to construct a pipeline for transmission of hydrogen from more distant production and storage centres (this can be limited to local distributed hydrogen network through pipelines).

Wherever feasible new residential, commercial, industrial and agricultural developments in areas not already served by the grid would be supplied by standalone energy supply and storage centres, namely 'autonomous hydrogen centers' (AHCs). RE sources would supply end-uses in all sectors directly so far as possible and the surpluses over direct demand would be converted to hydrogen for local and transiting road transport, and agricultural and industrial mobile machinery; and used in small-scale fuel-cell power plants to supply back-up electricity, and heat as well if needed, to houses, other buildings and agricultural and industrial enterprises, to guarantee continuous energy supply [24]. It is notable that the full unsubsidized cost of grid extension is already very high (some $10 000 per km in most parts of Australia), the minimum distance from the grid beyond which it may become viable to construct an AHC for a new development may often be only several kilometres.

4. Minimising hydrogen distribution network by complementary use of hydrogen and electricity

An important guiding principle in the design of a sustainable hydrogen system is to seek to minimise the extent of the required a national or even state/provincial wide hydrogen distribution network due to the high construction cost of a new hydrogen distribution network involving compressed hydrogen gas piped (required plant for pressurization). Such high costs of hydrogen distribution network could be a barrier against development of HE. For example it is undoubtedly the case that the apparently enormous investment required to set up a completely new hydrogen storage and distribution network has biased some policy makers against hydrogen as the alternative fuel for transport, and towards batteries charged from the existing grid where it has been thought that the infrastructure already exists. The central design feature to minimize the extent of the hydrogen pipeline network is to create a geographically distributed network of hydrogen production centres, so that so far as possible hydrogen is produced regionally or even locally for use or refueling vehicles, or energy storage for use in combined electricity and heating systems, in that same region or locality. Wherever practical, the long-distance transmission and distribution of the RE supply is via electricity. As Dougherty et al. [6] and McDowell and Eames [25] point out, decentralized production is one way to overcome many of the infrastructural barriers to a hydrogen transition. Along the same lines, Rifkin [26] and Sorenson [27] proposed decentralized or on-site hydrogen production actually in residential or commercial buildings, for refueling vehicles, and via fuel cells electricity and heat as well. Ideally, the only need for a hydrogen pipeline distribution system would be in major cities to transport hydrogen from bulk storage facilities (associated with off-shore, coastal or major inland hydrogen centres nearby) to [9]:

- a network of medium-sized hydrogen storages from which hydrogen could be transferred on demand (most likely by road tankers initially) to a network of refueling stations for road transport vehicles - cars, commercial vehicles and trucks
- facilities for producing liquefied hydrogen for use by aircraft (probably only one or two such facilities for each major city)
- hydrogen storages at major ports for refueling ships
- hydrogen storages at major railway terminals for refueling long-distance freight and passenger trains
- fuel cell power stations for supplying electricity to the grid at periods of low RE input, or during national emergencies that resulted in disruptions to normal supplies.

5. Roles for hydrogen as energy storage for transportation and stationary applications

5.1. Transportation

Both BEVs and hydrogen fuel cell vehicles (HFCVs) offer a completely zero-emission transport solution, provided the electricity to charge batteries, and electricity (or other energy source) to make the hydrogen, is also zero emission, that is, renewable, nuclear or fossil fuel with carbon capture and storage. At first sight, the energy efficiency from renewable source to traction energy for BEVs appears much higher than for HFCVs. The round-trip energy efficiency of a battery for short term storage (up to a few days) is likely to be in the order of 80%. For the hydrogen fuel cell system, the energy efficiency of the electrolyser is typically in the order of 90% (based on HHV), that for the storage 95%, and the fuel cell (HHV) 50%, giving a comparable roundtrip energy efficiency of only 43% [28-30]. This much lower round-trip efficiency has led some to dismiss the HFCV option outright in favour of BEVs [31]. However, if BEVs are left without being used for some time, the batteries will self-discharge and the round-trip efficiency will decline rapidly, towards zero over a period of several months. In addition, the BEV system charged from a grid will also require some longer term storage to guarantee supply throughout the year if the supply is substantially by variable renewables. Hence when the energy losses of this storage, which might ultimately be hydrogen based, are taken into account as well, the average round-trip energy efficiency of the overall BEV system will tend towards that of the HFCV route anyway.

The roles played by hydrogen and battery energy storages in transport applications in the future will in practice depend critically on the relative gravimetric and volumetric energy densities of the various storage materials and systems. In the case of hydrogen, the energy values have been converted to electrical energy equivalent assuming a fuel cell efficiency of 50% (based on HHV). But the corresponding energy densities for the various forms of hydrogen storage do not count the mass and volume of the fuel cell and associated equipment. Similarly most of the energy densities for batteries do not take account of the rest of the system.

On this basis, the current US DoE targets for hydrogen storage are for gravimetric energy density 0.89 kWhe/kg in 2010 (corresponding to 4.5%wt) and 1.09 kWh_e/kg in 2015 (5.5%wt). The corresponding targets for volumetric energy density are 0.55 kWhe/litre in 2010 (corresponding to 28 g of hydrogen per litre) and 0.79 kWhe in 2015 (40 g/L).

Compressed hydrogen tanks are approaching the energy densities required for vehicular applications (US DoE targets), but only if very high pressures are utilised. Hence here come a few barrier against it development such as: potentially-expensive refuling stations; public scepticism about it safety risks; and energy losses in compressing the hydrogen (up to 15% of the energy stored based on HHV for compression to 700 bar). Notably, liquid hydrogen is already able to meet the US DoE 2015 gravimetric energy target (1.09 kWh_e/kg) with its specific energy density typically in the range 1.0-1.3 kWh_e/kg, and exceeds the 2010 volumetric target (0.55 kWh_e/L) with its energy density in the range 0.630.69 kWe/L. But it just falls short of attaining the 2015 volumetric target (0.79 kWh_e/L). Cryo-compressed liquid hydrogen has been shown in tests to have both gravimetric and volumetric energy densities above the US DoE targets (1.46 kWh_e/kg and 0.89 kWh_e/L respectively) [32]. However, to liquefy hydrogen requires cryogenic cooling to 22 K, which can typically consume energy equivalent to 30-40 % of the energy content of the hydrogen stored [27], is required. Cryogenic storage tanks are also very expensive. Hence while liquid hydrogen is likely to be the most practical alternative fuel for jet and other aircraft, it is almost certainly too expensive and impractical for general automotive and other transport applications. Solid-state storage of hydrogen has major safety advantages, and generally requires much lower pressures, compared to compressed gas. Metal hydrides have been produced that can yield gravimetric densities in the range 0.30-0.47 kWh_e/kg (1.5-2.4 wt%), that is, between 35 and 50% of the 2010 US DoE target of 0.89 kWh_e/kg; volumetric densities in the range 0.35-0.47 kWhe/L, or between 65% and 87% of the US DoE 2010 target have been realised [32]. Some chemical hydrides (some solid and some liquids) have been found (for example, derivatives of ammonia borane or mixtures of this) with somewhat higher gravimetric densities, 0.55-0.65 kWh_e/kg (63-74% of the DoE 2010 target), and higher volumetric densities, 0.45-0.51 kWh_e/L (83-94% of the 2010 target). Hence metal and chemical hydrides currently do not match the performance of 350 and 700 bar compressed hydrogen cylinders in gravimetric density, but have already achieved volumetric densities exceeding 350 bar gas storage, and comparable to 700 bar storage. If the 2010 DoE target for metal or chemical hydrides is attained, these forms of storage will match the gravimetric energy density of 700-bar hydrogen gas storage, and exceed the corresponding volumetric energy density for the latter, without the need to charge and store hydrogen at such very high pressures.

The US Advanced Battery Consortium goals for batteries for electric vehicles, most likely lithium ion, are 0.15-0.20 kWhe/kg for gravimetric energy density and 0.23-0.30 kWh_e/L for volumetric energy density[33]. Chalk and Miller [34] reported that the best lithium ion batteries have already achieved gravimetric energy densities of 0.12 kWh_e/kg (80% of the target), and volumetric energy densities of 0.14 kWh_e/L (80% of the target). However, the recently developed A123 lithium ion battery pack has a gravimetric energy density (system) of 0.057 kWh_e/kg , and a volumetric energy density of 0.098 kWh_e/L [1].

Looking to goals set for technological advance, the US DoE [32] target for the gravimetric energy density for hydrogen storages in 2015 is just over 3.5 times that set by US DoE EERE [1] for batteries for plug-in petrol electric hybrid vehicles (64 km range), and the corresponding advantage of hydrogen for volumetric energy density is 1.8. Hence hydrogen storage currently has, and will probably extend in the future, a substantial advantage over batteries in gravimetric and volumetric energy densities when used in vehicles with a range similar to that of today's petrol and diesel vehicles. Other things being equal, this advantage should mean that hydrogen fuel cell vehicles will have a much greater range (two to three times) that of a comparable battery electric vehicle for a given volume and mass of the storage system. However, a necessary condition for use of hydrogen for transport in a sustainable energy strategy is that hydrogen storage maintains a substantial advantage over battery storage in terms of gravimetric and volumetric energy densities. The optimal energy storage system for vehicles requiring a range equivalent to today's petrol and diesel vehicles is actually likely to employ a combined hydrogen and battery system. The hydrogen system would provide the bulk energy storage, while a relatively small energy capacity battery would allow regenerative braking, meet peak power demands, and generally buffer the fuel cell against load changes to extend its lifetime. This complementary use of hydrogen and battery storage is precisely the arrangement employed by Honda in its FCX Clarity hydrogen car that is now available commercially in limited numbers. The complementarity of hydrogen and battery storage may well be extended to the question of which type of vehicle is best across a range of transport applications.

5.2. Stationary application

Renewable energy sources are inherently intermittent and variable; however, reliance on a joint probability distribution for the supply of power from a diverse range of types and locations of RE generators, each subject to its own probability distribution over an annual period, should indeed give a greater continuity and reliability of supply than that obtainable from a small number of very large renewable power stations. A finite probability of low supply will still remain that creates a need for reliable energy storage system. Options such as batteries, supercapacitors, and thermal storage - that essentially provide just short term storage (from seconds to a few weeks) - are valuable considering the diurnal cycle of solar radiation. However, particularly in locations with high seasonal variations in RE input a longer-term form of storage such as hydrogen will probably still be necessary for security of supply and advantageous economically. As another storage option, Pumped hydroelectric schemes in which surplus power is used to pump water to the high reservoir of a hydroelectric facility, and then allowed to run back to the lower reservoir through the turbines at times of supply shortage, offer a reasonably high roundtrip energy efficiency (above 70%). However, the global availability of additional environmentally-acceptable sites for such schemes, which require very large reservoir capacities, is generally now very limited. Even at 100% energy conversion efficiency and 100 m head the volumetric energy density of pumped hydroelectric storages is only 0.273 Wh_e/litre, compared to up to 0.47 kWh_e/L achieved with metal hydrides and fuel cells.

To investigate the capability of hydrogen to play energy storage role, we have developed a novel dimensionless approach to analysing the capability of a solar electricity supply system with seasonal hydrogen storage to supply a continuous and constant load throughout the year with a much lower installed solar capacity than the same system without storage [35]. The only input required specific to the location is its solar ratio, defined as the minimum daily solar energy input during the year divided by the maximum. As well as yielding an estimate of the saving in installed primary solar electricity generating capacity, the approach is extended to give an indicative evaluation of the likely economic viability of adding the hydrogen storage to a photovoltaic-based solar supply. The dimensionless model is applied to a selection of 78 cities with varying latitudes across all five continents. For a round-trip energy efficiency of hydrogen storage of around 45% and the base case unit costs of components assumed, solar-hydrogen systems would be economic in 55% of these cities, with economic viability generally (but not always) increasing with the latitude of the city. If the round-trip energy efficiency could be raised to 50%, and/or the unit costs further reduced, solar-hydrogen systems would become viable in the vast majority of the cities, excepting those nearer the equator with very high solar ratios in excess of 80%.

6. Australia and the sustainable hydrogen economy

6.1. Renewable energy in Australia

Hydro, wind, bioenergy, solar, geothermal and ocean are the key RE sources/technologies currently available to produce renewable power in Australia [36]. Australian production of renewable energy (including electricity generation, conversion losses and direct fuel use) is dominated by hydroelectricity, bagasse, wood and wood waste, which combined accounted for about 85 per cent of Australian renewable energy production in 2008–09 (Fig. 3). Wind energy, solar energy and biofuels (which include landfill and sewage gas) accounted for the remainder of Australian renewable energy production. Most solar energy is used for residential water heating and accounts for 1.8 per cent of final energy consumption in the residential sector [37]. Australian production of renewable energy has been increased by 11% between 2004 and 2009 with over 5% of this increase happened between 2007-8 and 2008-9 (Fig 4). Solar electricity (the smallest contributor) experienced the strongest growth in 2008–09, increasing by 40%. Solar hot water also increased strongly, with a 27% increase from 6.5 petajoules in 2007–08 to 8.2 petajoules in 2008–09. Despite such an increase in the total renewable energy production in Australia (11% between 2004 and 2009), the share of renewable energy consumption in compared with the other primary sources of energy consumption has not been increased significantly during the past years (Fig. 5) (it has been reported to be 5.2% of total primary energy consumption in 2008-2009).

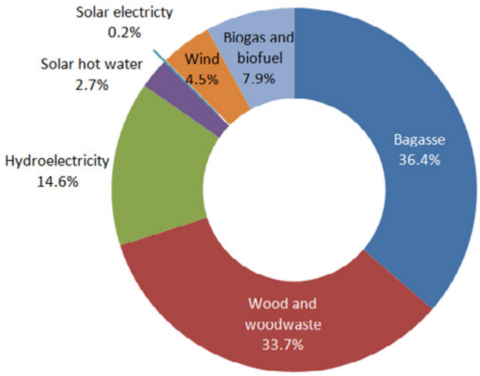

Fig. 3 Distribution of Australian renewable energy production (2008-2009) [37]

According to ABARES [37], Australia has produced 19.2 TWh of its electricity through renewable energy sources in 2009 out of a RE electricity generation capacity of over 10000 MW. This is about 7.4% of the total electricity generated in Australia in 2008-9 (Fig. 6). This percentage used to be about the same back in 2004-5. According to the Australian energy projections to 2029-30 released by ABARES [38] the share of electricity generation from RE sources is predicted to increase to about 20% in 2029-30. It is also predicted by the same source [38] that the share of RE sources in total primary energy consumption by fuel, which has been reported to be just over 5% in 2008-9, will increase to nearly 8% by 2029-30.

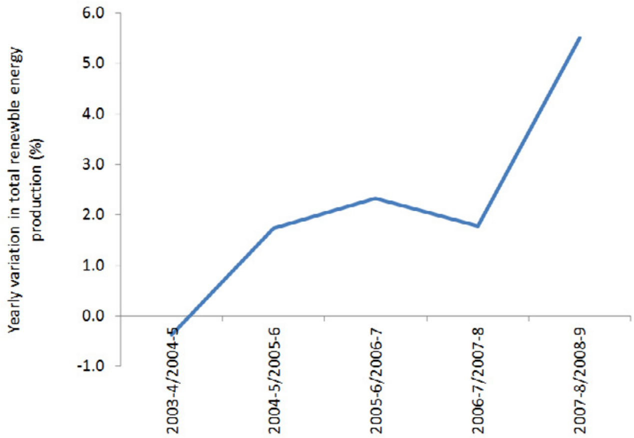

Fig. 4. Percentage of yearly variation of renewable energy production in Australia; data source [37]

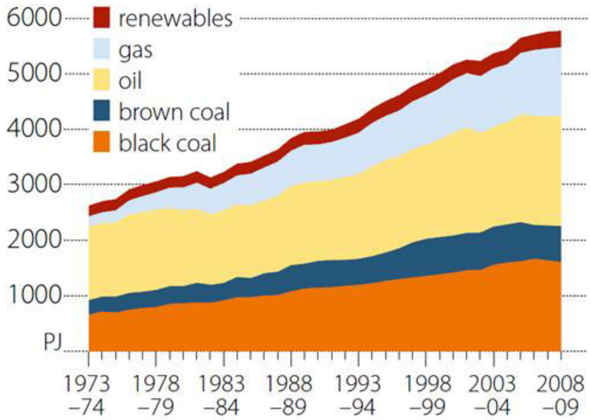

Fig. 5. Primary energy consumption trend in Australia [37]

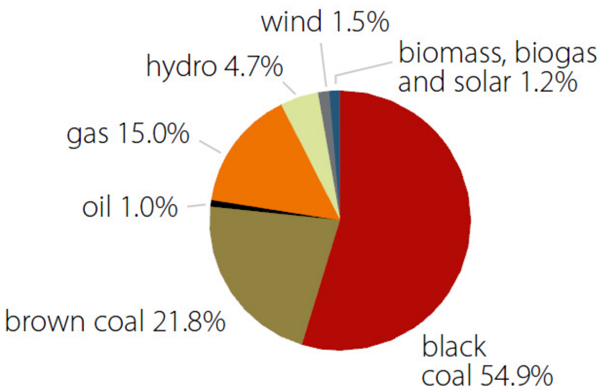

Fig. 6 Australian electricity generation by fuel in 2008-9 [37].

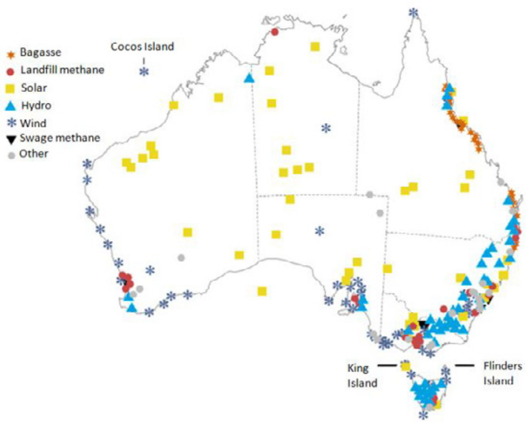

Fig. 7 Renewable energy generators in Australia; Source: [37] taken originally from Geosciences Australia

6.2. Prospects for a hierarchy of hydrogen centres in Australia

Despite the vast landmass, approximately 50% of Australia's population lives in majors cities (Sydney, Melbourne, and Brisbane) on the narrow strip of coastline on the East [36]. The current capacity of renewable energy production is also more concentrated on coastal areas (Fig. 7). This is an ideal situation for decentralised utilisation of RE sources.

Despite the high potential of Australia for extracting solar energy (in particular inland solar electricity production) just a small portion of already low renewable energy deployment in Australia is made by solar electricity production (e.g. solar electrify accounts for just less than 2% of total RE electricity generation capacity in Australia).

High availability of solar energy, particularly in the middle part of Australia, existing isolated communities with no connection to the main grid (considering already high cost of grid extension), and high population distribution along the coasts suggest the suitability of all types of hydrogen centres, introduced in Fig. 2, for Australia in the sustainable hydrogen economy depicted in this paper.

6.3. Barriers against renewable energy development in Australia

Despite possessing a very large potential of renewable energy sources, Australia has lagged behind other developed countries in using its RE sources [39]. The Australian Government's Mandatory Renewable Energy Target (MRET) introduced in 2001, the expanded RET began on 1 January 2010, committing the Australian Government to a target of 20% of Australia's electricity supply coming from renewable energy sources by 2020 are some of the measures taken to support development of renewable energy in Australia. Effendi and Courvisanos [39] tried to explain the barriers against development of renewable energy in Australia using a Political Aspect of Innovation (PAI) framework. Using this PAI framework they showed that the political barriers against the growth of renewable energy in Australia use the existing technical difficulties as camouflage in their attempts to slow down taking up RE technologies. The high capital cost of creating the infrastructure and the lack of reliability of supply through intermittent RE power to a centralised grid are some of these key technical problems. However, these problems could be illuminated by adopting a decentralised hydrogen/RE-based power distribution system in a sustainable HE model introduced and discussed comprehensively in this paper.

7. Conclusion

In this paper the role of hydrogen in a sustainable energy strategy broadly applicable at national and international levels was discussed. Irreversible climate change, uncertain oil supply, and rising pollution levels of diverse kinds, along with the strong challenges to hydrogen were the key things considered in this discussion.

RE inputs are ideal for the sustainable energy strategy proposed in this paper while taking energy efficiency to its economic limits. Complementary use of hydrogen and electricity as energy vectors as well as hydrogen and battery in transport sectors are emphasized in the sustainable hydrogen economy discussed in this paper. Hydrogen would be produced, stored and consumed locally so far as practical, rather than being produced at a few large-scale facilities and then transmitted via long-distance pipelines centralized to distant cities as given in the original hydrogen economy concept (hydrogen pipelines would be still required for some local distributions). Bulk hydrogen storage would, however, provide the strategic energy reserve to guarantee national and global energy security in a world relying increasingly on RE.

A quantitative scenario for a transition to a hydrogen-based sustainable energy strategy over time will need to be developed for Australia using an appropriate energy-economic model. Using such a model an evaluation can be conducted into the overall economic, environmental and social benefits of the HISE strategy compared with alternative scenarios. The role of hydrogen in a sustainable energy economy now deserves full and urgent consideration in terms of policy studies, and research, development, demonstration and commercialization of the enabling technologies.

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